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Identifying fast hadrons with silicon detectors

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Chapter 1

Introduction

Particle detectors have always been extremely important in high-energy and nuclear physics experiments because the human senses are not suited to detect the invisibly small particles involved in these experiments. There is a nice synergy between experimental research at the frontier of science and detector development since new or improved detection techniques enable on the one hand more sophisticated experiments, while on the other hand, the need for advanced experiments is a driving force for the development of ever better detectors.

The earliest particle detectors that were used around the turn of the 20th century were photographic emulsion and phosphorescent screens. The latter are the precursors of scintillation detectors. A gas filled radiation detector was invented by Geiger in 1908 and it enabled electronic registration of the counter signals. With the invention of the photomultiplier tube in 1930 also scintillation signals could be efficiently recorded in counting experiments.

The discovery of semiconductor detectors, more than sixty years ago, was another major breakthrough for particle physics experiments. It started in 1945 with the observation of electrical signals in silver-chloride crystals [1] when they were irradiated by α-particles, electrons or X-rays. This observation was followed by similar measurements on diamond and germanium crystals [2, 3]. However, due to the poor charge collection efficiency of the crystals, which was caused by trapping and recombination effects, it took almost ten years before semiconductor crystals were applied in counting applications. By that time, high purity silicon and germanium crystals could be produced, which showed a better energy resolution compared to the gaseous and scintillating type detectors. Hence, the main applications for these semiconductor detectors were nuclear, alpha, neutron and gamma spectroscopy [4]. The semiconductor detectors in those days consisted of small crystals with an area of typically less than 1 cm^2. It is interesting to note that already in 1962 silicon detectors were applied for identifying slow protons, deuterons and helium nuclei [5] by measuring their energy deposition. Another technique that was used for identifying particles with silicon is pulse shape discrimination [6], but this is only applicable for low energy particles.

The first monolithic segmented detectors appeared in 1961 [7], providing position information in addition to the energy deposition signal. In 1966 a Dutch group [8] constructed the first double-sided detectors by depositing a pattern of gold strips on the front surface, and aluminium strips in the orthogonal direction on the back surface. This 'checkerboard' detector was the first true two-dimensional silicon detector. However, is was not until the early 1980s that highly segmented position sensitive detectors (microstrip detectors) became commonly used in high energy physics experiments. Especially, the research on short-lived particles for which high precision track information is required [9] pushed the development of silicon detectors. These detectors were used to detect minimum ionizing particles and were shown to be suited for reconstructing the position of the interaction and the decay vertex. The sensitive area of the silicon microstrip sensors used was 20×30 mm^2 and the strip pitch was 200 μm.

With the introduction in 1982 of Charge Coupled Devices (CCD) in high energy physics experiments [10], a new technique was introduced which provided high precision monolithic two-dimensional detectors. This development was followed in 1989 by hybrid pixel detectors in which the sensitive highly segmented detector is attached to a multichannel readout chip by means of bump bonding. These hybrid pixel detectors are essential in high count-rate applications where microstrip or CCD sensors cannot be used. More recent developments also include monolithic active pixel sensors in which the sensitive detection layer is integrated into the same wafer as the associated readout electronics. Although these monolithic pixel sensors became popular relatively recently, they were already proposed in 1988 [11].

Nowadays every major high energy physics experiment uses silicon strip and pixel (hybrid or CCD) detectors in the first detector layers surrounding the interaction point. In the largest experiments these detectors consist of several millions strips and almost a hundred million pixels [12]. Single silicon sensors are constructed from crystals with a surface area as large as 10×10 cm^2, and readout of the sensors is accomplished by custom developed integrated circuits. The main goal of semiconductor detectors in these experiments is to provide accurate spatial coordinates in order to reconstruct the tracks in the vertex region with a resolution of several micrometers. Even though the energy deposition of the particles in the detectors is almost always measured, the information is only used to improve the resolution of the particle tracks.

One branch of experimental particle physics where silicon detectors were hardly used until recently is the investigation of the quark-gluon structure of the nucleon [13, 14]. By scattering high-energy leptons off nuclear targets these experiments have, over the years, accurately determined the momentum distribution of the quarks and gluons in the nucleon, and more recently the contribution of the quark spins to the nucleon spin [15]. However, the sum of all experimentally determined contributions to the nucleon spin do not add up to precisely $\frac{1}{2}\hbar$ which is the spin of the nucleon as a whole. Therefore, an additional contribution to the nucleon spin is required, which could come from the gluon spin [16] or the orbital angular momentum of the quarks and gluons. In order to quantify the latter contribution, new experiments are needed which must be operated at new high luminosity facilities and which use high-density polarized targets.

The best way to gather information on the orbital angular momentum of the quarks in the nucleon is by studying the Deeply Virtual Compton Scattering (DVCS) process which requires measurements enabling the identification of exclusive processes. Unfortunately, the resolution of the main forward spectrometer in such deep inelastic scattering experiments is typically about 1%, which is not enough to ascertain the exclusivity of these processes. The latter requirement can be accomplished by making use of an additional detector in the target area of the experiment. Such a so-called recoil detector must detect and identify the relatively low-energy hadrons that emerge from the final state of the interaction (and background processes). Given the many constraints in the target area of such an experiment, the use of silicon detectors to accomplish this task is likely to be the best option, especially if it can be proved to be possible to identify recoiling protons up to momenta of 1.3 GeV$\cdot$c^{-1}. In this thesis it is investigated to what extent a recoil detector consisting of only a few layers of silicon detectors can be used to identify recoiling protons in DVCS measurements at future high-intensity DIS facilities. For this purpose several detector techniques are compared, Monte Carlo simulations are performed for the chosen solution and an experiment has been performed at CERN to investigate the particle identification capability of the proposed detector concept.

This thesis is organized as follows. In chapter 2 the key concepts of Deep Inelastic Scattering are introduced including a discussion on how the contribution of the orbital angular momentum of the quarks to the nucleon spin can be measured. In that light, the concept of generalized parton distributions is introduced which provides the mathematical framework to access the orbital angular momentum via the observation of exclusive processes. The second part of this chapter elaborates on the experimental environment that is needed to conduct such experiments. More specifically the possibility of employing a recoil detector in the target area is addressed. The influence of background events, which are numerous due to the use of a dense target, are also discussed in some detail.

Chapter 3 starts with an overview of the various detection techniques that can be used for particle identification, followed by a detailed discussion of energy deposition measurements in silicon. This chapter also gives the necessary background for dE/dx measurements with silicon detectors. The statistical analysis methods, which are used in dE/dx-based particle identification procedures and which are used in the remaining chapters, are also discussed.

The subject of chapter 4 is the Monte Carlo study which has been done to determine whether a recoil detector at a future fixed-target deep inelastic scattering experiment can be built from a stack of silicon detectors only. The simulations are used to explore the various detector configurations and to predict its particle identification capabilities. Realistic models for both the silicon sensors and the readout electronics are used in terms of charge collection efficiency and noise. The benefits and drawbacks of operating a silicon recoil detector in a magnetic field, which will be present in the (polarized) target region of such an experiment, are also discussed.

Chapter 5 describes an experiment that has been conducted at CERN in order to confirm the particle identification capabilities of a multi-layer silicon telescope in the momentum range of 0.8 to 1.3 GeV$\cdot$c^{-1}. The chapter begins with a description of the experimental set-up and is followed by a discussion of the analysis of the data from a time-of-flight system consisting of four scintillators. This time-of-flight system provides independent particle identification which is needed to qualify the performance of the dE/dx silicon telescope. The second part of this chapter deals with the analysis of the data obtained with two different sets of four double-sided silicon detectors that were used in the experiment. These detectors provide the dE/dx information for the particle identification which is the last subject in this chapter.

Finally, chapter 6 gives the conclusions of the studies presented in this thesis. Furthermore, an outlook is given on those aspects of this study that need to be pursued in the future in order to come to a complete conceptual design of a full scale recoil detector that can be used in future experiments aimed at measuring the parton orbital angular momentum in the nucleon.